HabEx

# The Habitable Exoplanet Observatory (HabEx) Decadal Mission Study

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# Study Goals

**“Develop an optimal* mission concept for characterizing our nearest planetary systems, and detecting and characterizing a handful of ExoEarths.”**

**“Given this optimal* concept, maximize the astrophysics science potential without sacrificing the primary exoplanet science goals.”**

***What does optimal mean?**

- Maximizing the science yield while maintaining feasibility, i.e., adhering to expected constraints.
- Constraints include: Cost, technology (risk), time to develop mission.

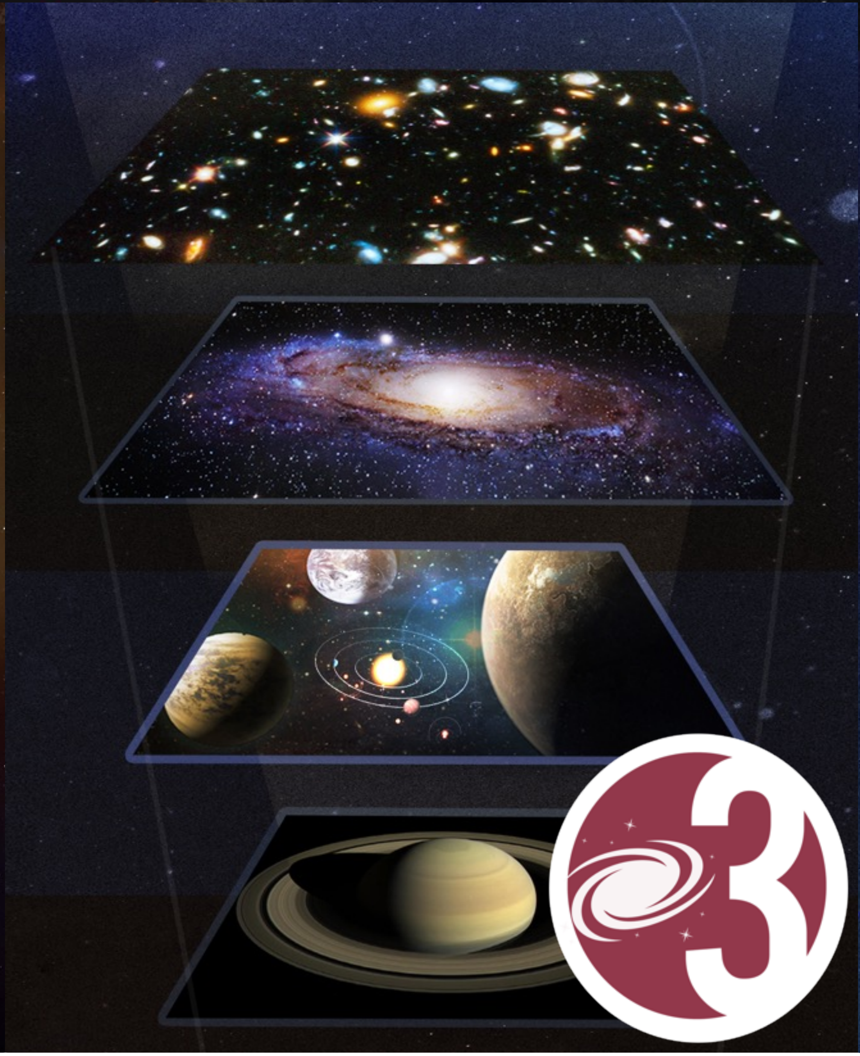
HabEx

# Science Goals

NASA


Seek out nearby worlds and explore their habitability

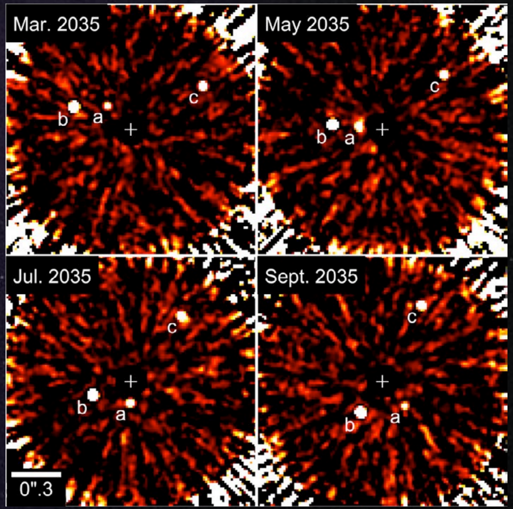

Map out nearby planetary systems and understand their diversity.




Enable new explorations of systems in the UV to near-IR

# Exoplanet Detection and Characterization

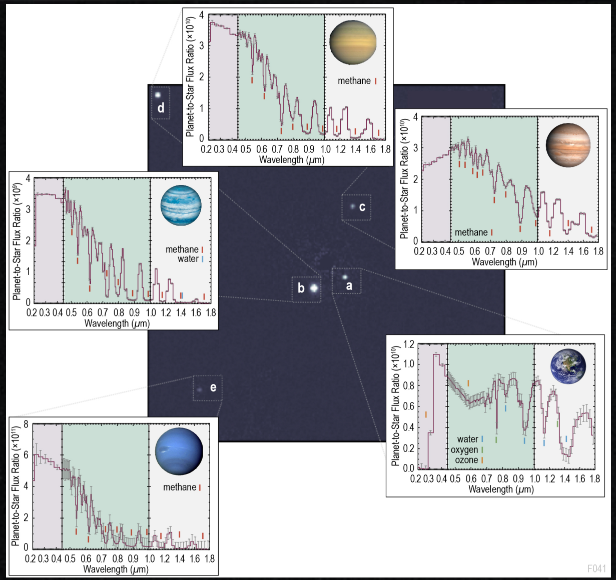
## Coronagraph detects:




Star system at 7.5 pc,
orbital inclination 60 deg,
0.45-0.55μm, 1.5x1.5 asec FOV

(a) exo-Earth analog (1 AU)
(b) Sub-Neptune analog
(c) Jupiter analog

Credit: G. Ruane.



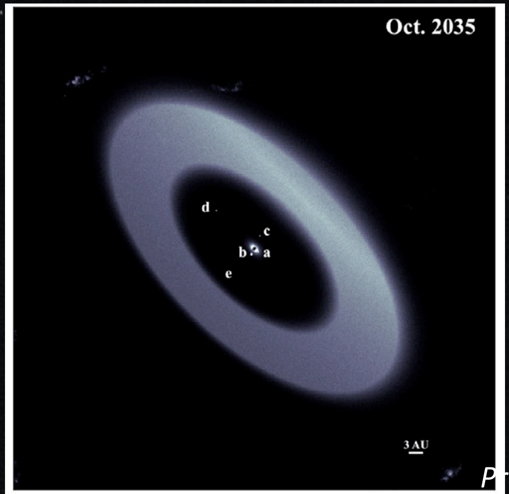

Starshade characterization first with Visible, followed by far-UV and near-IR

## Starshade characterizes:

Same as above, except with 11.9 x 11.9 asec FOV revealing outer planets and dust belt:

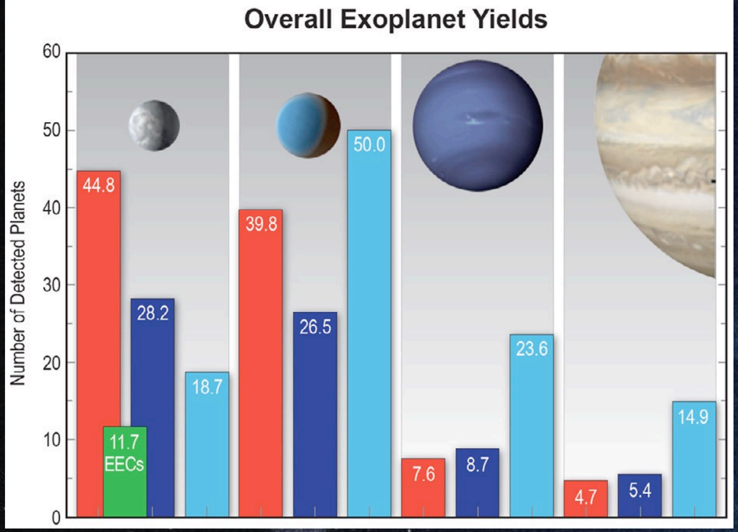
(a) exo-Earth analog
(b) sub-Neptune analog
(c) Jupiter analog
(d) Saturn analog
(e) Neptune analog

Credit: S. Hildebrandt



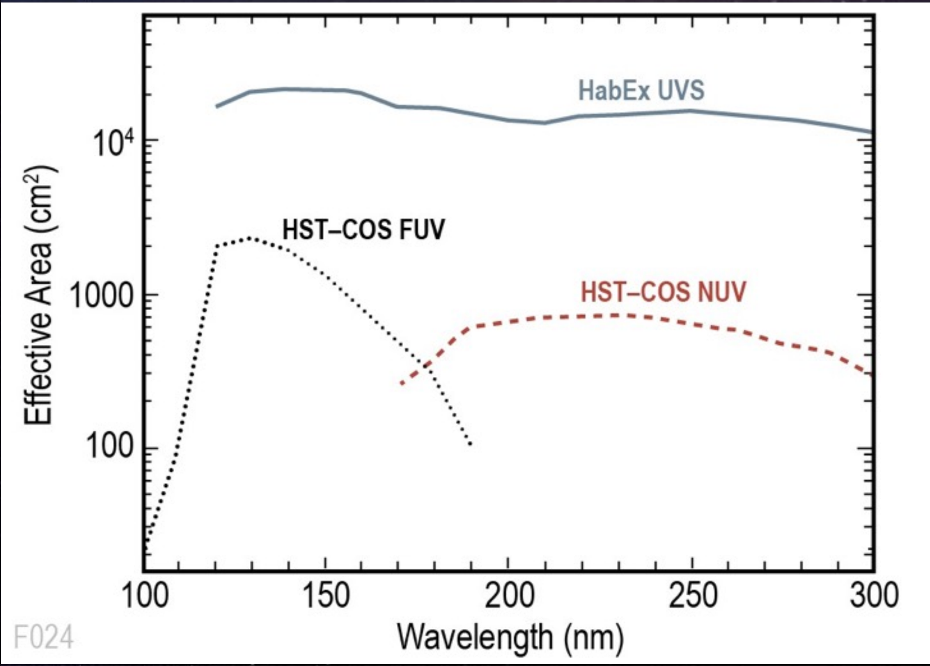

HabEx is expected to detect 200+ exoplanets:
- 92 rocky planets,
  - ~***12 Earth analogs***,
- 116 sub-Neptunes,
- 65 gas giants.

*based on SAG13 occurrence rates for each planet size and stellar insulation level. Occurrence rates estimates are highly uncertain for cold planets.

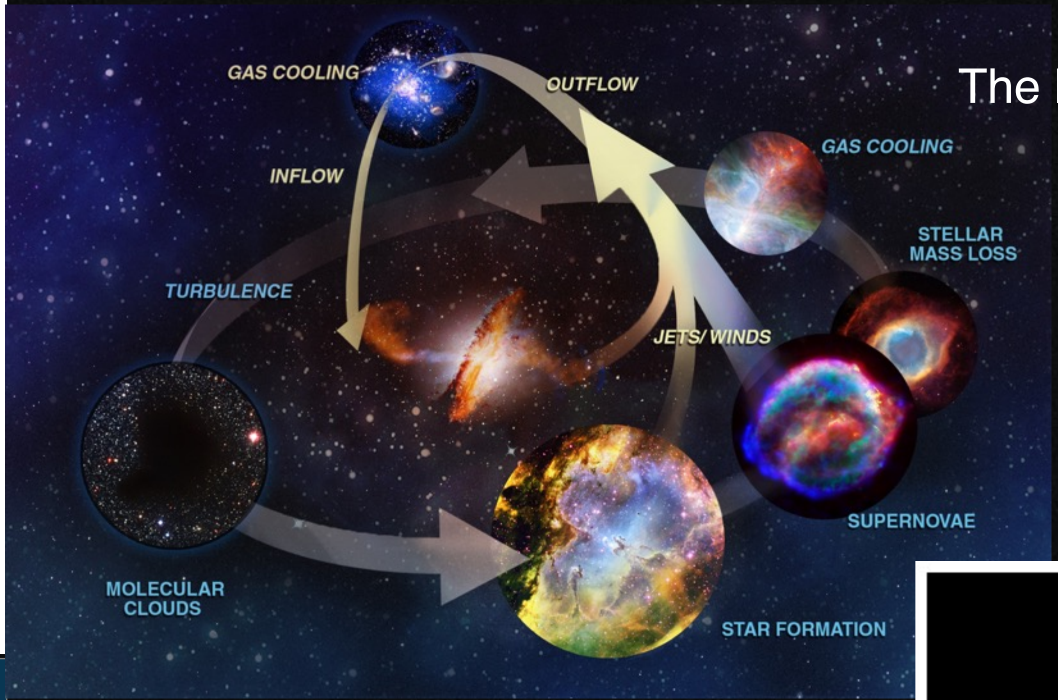


# HabEx

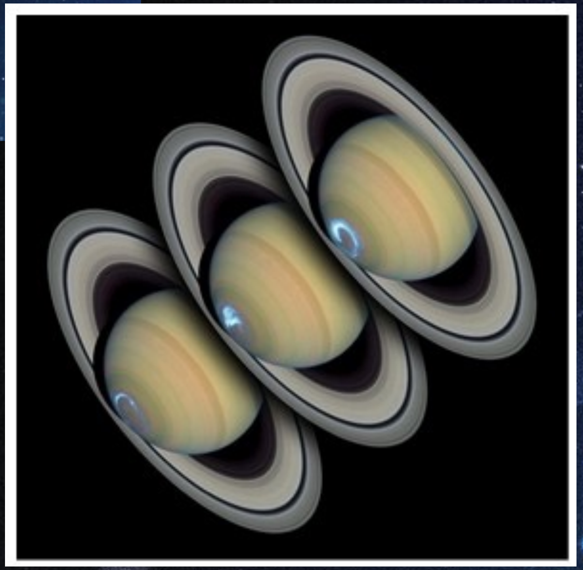
# Next Generation Guest Observatory




| | Ultraviolet Spectrograph (UVS) |
|---|---|
| **Field-of-view** | 3 x 3 arcmin$^2$ |
| **Wavelength bands** | 20 bands covering 0.115 to 0.3 μm |
| **Spectral resolutions** | 60,000; 25,000; 12,000; 6,000; 3,000;1,000; 500 |
| **Telescope resolution** | Diffraction limited at 0.4 μm |
| **Detector** | 3x5 MCP array, 100mm sq each |
| **Array width** | 17,000 x 30,000 pixels (pores) |
| **Microshutter array** | 2x2 array of 171x365 200x100 μm apertures |

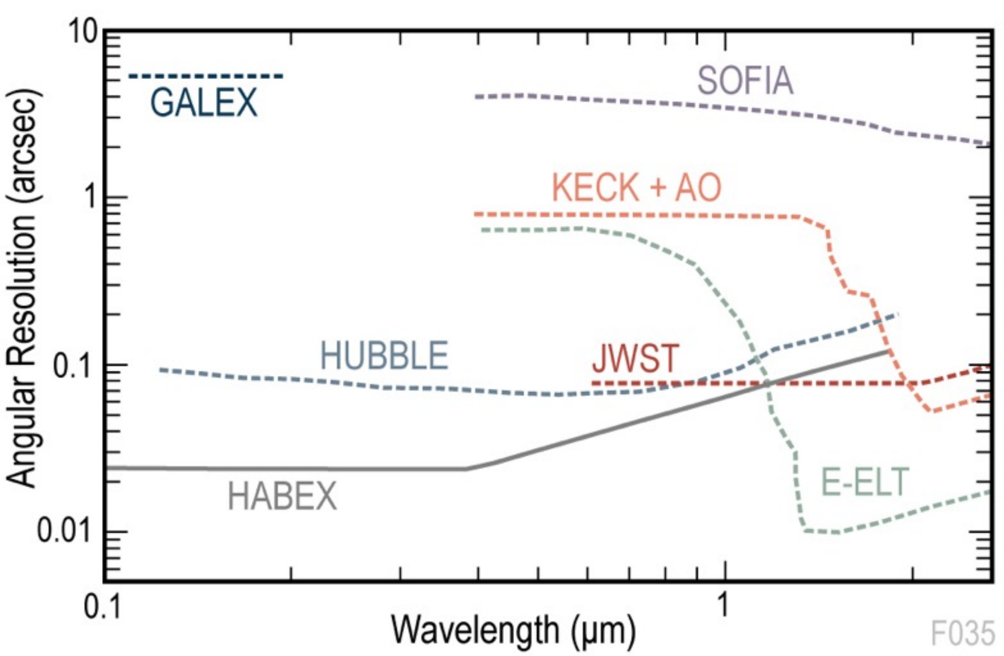



The lifecycle of baryons

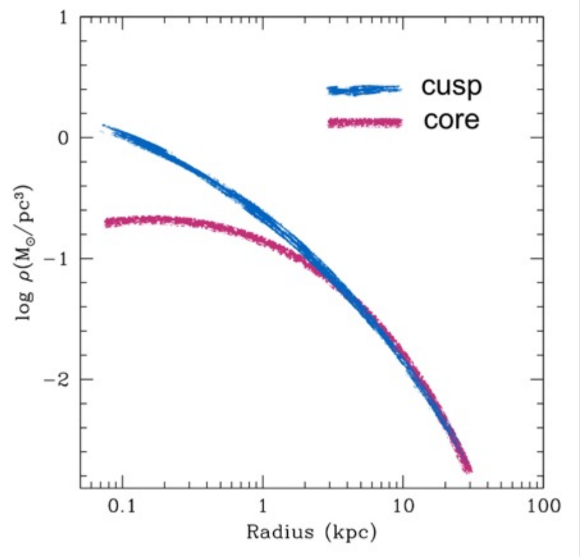


Solar System Aurorae

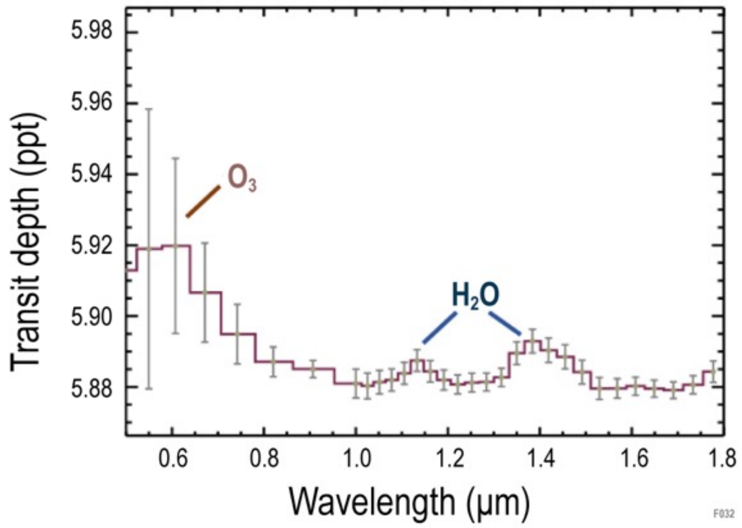
# HabEx Next Generation Guest Observatory




| HabEx Workhorse Camera (HWC) | UV/Vis Channel | near-IR Channel |
|---|---|---|
| Field-of-view | 3 x 3 arcmin$^2$ | 3 x 3 arcmin$^2$ |
| Wavelength bands | 0.15 – 0.95 μm | 0.95 – 1.8 μm |
| Spectral resolution | 2000 | 2000 |
| Telescope resolution | 30.9 mas | 49 mas |
| Detectors | 3x3 CCD203 | 2x2 H4RG10 |
| Array width | 12,288 pixels | 8,192 pixels |
| Microshutter array | 2x2 arrays; 200x100 μm aperture size; 171x365 apertures | |


Dark matter in dwarf galaxies




Exoplanet Transit Spectroscopy

# HabEx Architecture A Concept

- The HabEx STDT chose these parameters for Architecture A:
  - Telescope with a 4m aperture
  - 52-m diameter, formation flying external Starshade occulter
  - Four instruments:
    - Coronagraph Instrument for Exoplanet Imaging
    - Starshade Instrument for Exoplanet Imaging
    - UV – Near-IR Imaging Multi-object Slit Spectrograph for General Observatory Science
    - High Resolution UV Spectrograph for General Observatory Science

- Mission duration:
  - 5 years,
  - consumables for 10 years
- Orbit: Sun-Earth L2 Halo
- Bandpass:
  - Far UV through Near IR (115nm – 1800nm)
- Defined Exoplanet Science Program: ~50%
- GO/General Astrophysics Science Program: ~50%
- Telescope Flight System is serviceable
- Starshade Flight System may be refuelable (but otherwise not serviceable)
  - Degradation due to micro-meteoroids
- Capable of non-sidereal tracking of planetary objects


*Image from HabEx interim report URS273294*

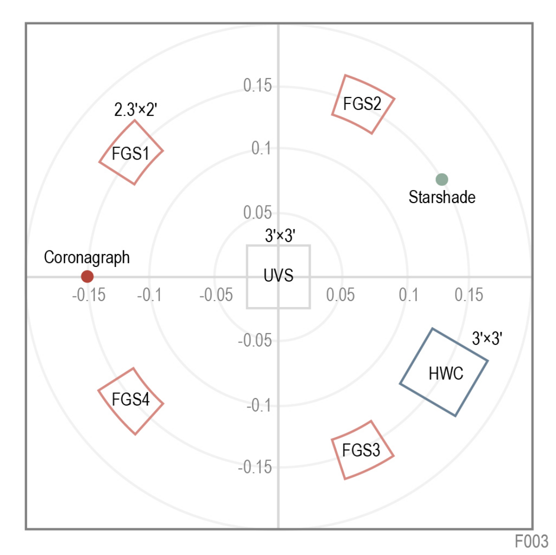
# HabEx Instrument Specs

## Coronagraph

| Cameras | Blue Channel | Red Channel | IR Channel |
|---|---|---|---|
| FOV | 1.5 asec | 2.2 asec | 3.1 asec |
| Wavelength bands | 0.45–0.55 µm<br>0.55–0.67 µm | 0.67–0.82 µm<br>0.82–1.0 µm | 0.95–1.8 µm |
| Pixel resolution | 11.6 mas | 17.3 mas | 29.9 mas |
| Telescope resolution | 23 mas @ 0.45µm | 35 mas @ 0.67µm | 49 mas @ 0.95µm |
| IWA (2.4 λ/D) | 56 mas @ 0.45µm | 83 mas @ 0.67µm | 118 mas @ 0.95µm |
| OWA | 0.74 asec | 1.11 asec | 1.57 asec |
| Detector | 1×1 CCD201 | 1×1 CCD201 | 1×1 LMAPD |
| Array width | 1024 | 1024 | 256×320 |
| **Spectrometers** | **Blue Channel** | **Red Channel** | **IR Channel** |
| FOV | 1.5 asec | 2.2 asec | 3.1 asec |
| Spectrometer resolution λ/Δλ | 140 | 140 | 40 |
| Spectrometer type | IFS | IFS | Slit |
| Detector | 1/4 CCD282 (EMCCD) | 1/4 CCD282 (EMCCD) | 1×1 LMAPD |
| Array width (pixels) | 2048 | 2048 | 256×320 |
| Deformable mirror | 64×64 0.4 mm pitch | 64 × 64 0.4 mm pitch | 64×64 0.4 mm pitch |

## Starshade

| Science Band | UV | Visible | IR |
|---|---|---|---|
| Bandpass | 0.2-0.667µm | 0.3-1.0µm | 0.54-1.8µm |
| Separation | 114,900 km | 76,600 km | 42,500 km |
| IWA (@ longest λ) | 47 mas | 70 mas | 126 mas |
| **Cameras** | **UV Channel** | **Visible Channel** | **IR Guide Channel** |
| FOV | 10.2 asec | 11.9 asec | - |
| Bandpass | 0.2-0.45µm | 0.45-1.0µm | 0.975-1.8µm |
| Pixel resolution | 14.2 mas | 14.2 mas | 12 cm (lateral) |
| Telescope resolution | 21 mas | 21 mas | - |
| IWA (@ longest λ) | 47 mas | 70 mas | 126 mas |
| Detector | 1x1 CCD201 | 1x1 CCD201 | 1x1 LMAPD |
| Array width (pixels) | 1024 | 1024 | 256 |
| **Spectrometer** | **UV Channel** | **Visible Channel** | **IR Guide Channel** |
| FOV | 10.2 asec | 1.9 asec | 3.8 asec |
| Bandpass | 0.2-0.45µm | 0.45-1.0µm | 0.975-1.8µm |
| Spectral resolution | 7 | 140 | 40 |
| Spectrometer type | Slit/grism | IFS | IFS |
| Detector | 1x1 CCD201 | 1x1 CCD282 | 2x2 LMAPD |
| Array width (pixels) | 1024 | 4096 | 2048 |




## UVS

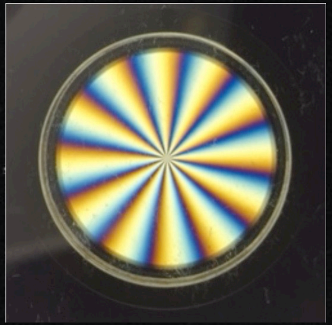
| High Resolution UV Spectrograph | |
|---|---|
| FOV | 3 amin x 3 amin |
| Spectral bands | 20 bands covering<br>0.115 to 0.3 µm |
| Spectral resolution | 60,000 |
| Telescope resolution | 400 nm diffraction limit |
| Detector array width | 3x5 MCP array, 100mm sq each<br>17,000 x 30,000 pixels (pores) |
| Microshutter aperture array | 2x2 array of 171x365<br>200x100µm apertures |

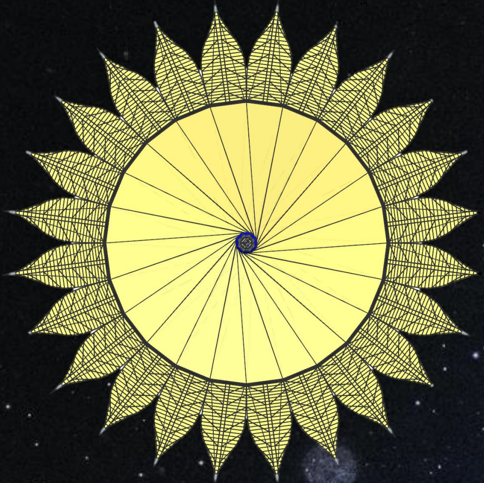
## HWC

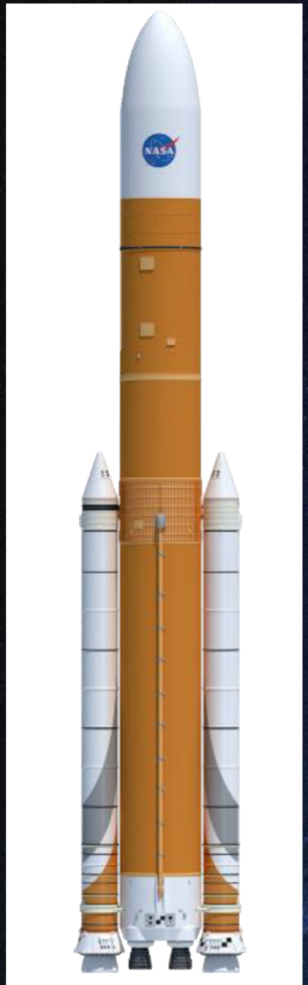
| HWC | UV/Vis Channel | IR / Vis Channel |
|---|---|---|
| FOV | 3 amin x 3 amin | 3 amin x 3 amin |
| spectral bands | 0.15 - 0.95 µm | 0.95 - 1.8 µm<br>(goal: 2.5µm) |
| Pixel resolution | 15.5 mas | 24.5 mas |
| Telescope resolution | 30.9 mas | 49 mas |
| Design wavelength | 0.6 µm | 0.95 µm |
| Detector | 3x3 CCD203 | 2x2 H4RG10 |
| Detectror array width | 12,299 pixels | 8,192 pixels |
| Spectral resolution | 2000 | 2000 |
| Microshutter array | 2x2 array of 171x365<br>200x100µm apertures | |

# HabEx Key Features:

- These features are “game changers” that enable this observatory concept:
  - SLS Block 1B Launch Vehicle with 8.4m x 27.4m Fairing
    - *Characteristic*: Increased mass and volume launch capability over existing LVs
    - *Benefit*: Allows the use of mass and volume to minimize complexity and therefore reduce risk and cost
  - Microthrusters
    - *Characteristic* : Extremely low mechanical disturbance noise
    - *Benefit* : Significantly improves pointing stability, simplifies structural dynamics design, improves telescope wavefront stability
  - Vector Vortex Coronagraph (VVC)
    - *Characteristic* : much less sensitive to low order wavefront aberrations with high throughput
    - *Benefit* : Reduces the need for an ultra stable telescope.
  - Starshade occulter
    - *Characteristic* : allows for a small inner working angle (IWA) over a broad spectral band
    - *Benefit* : Allows a 4m telescope to have an IWA equivalent to a much larger one, in this case: 7.1m telescope @ $\lambda$=1$\mu$m







***SLS Block 1B Cargo***

# Why the SLS?

- Keep it simple!
- Use mass and volume to minimize complexity:
  - Minimize deployments
    - Fewer mechanisms and control electronics.
  - Use volume for a 4m unobscured, off-axis telescope with Instruments on the side (not under the PM).
  - Use mass for a monolithic Zerodur® primary mirror.
    - CBE: 1295kg, 80Hz first mode
    - very high thermal inertia for stability

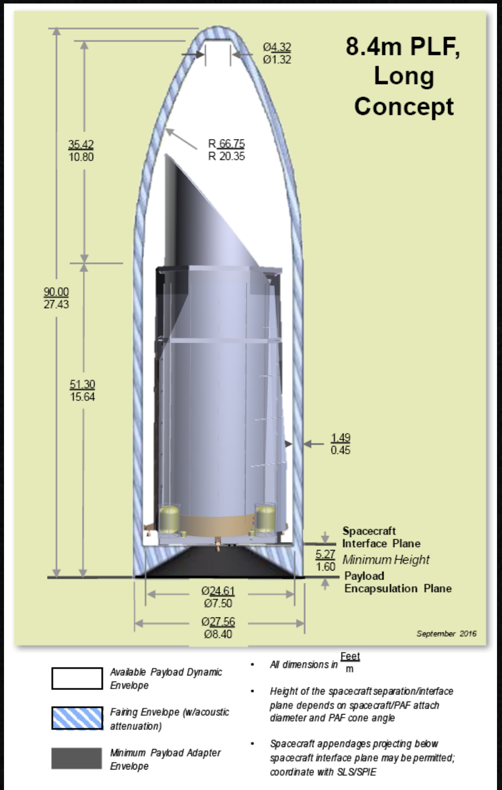
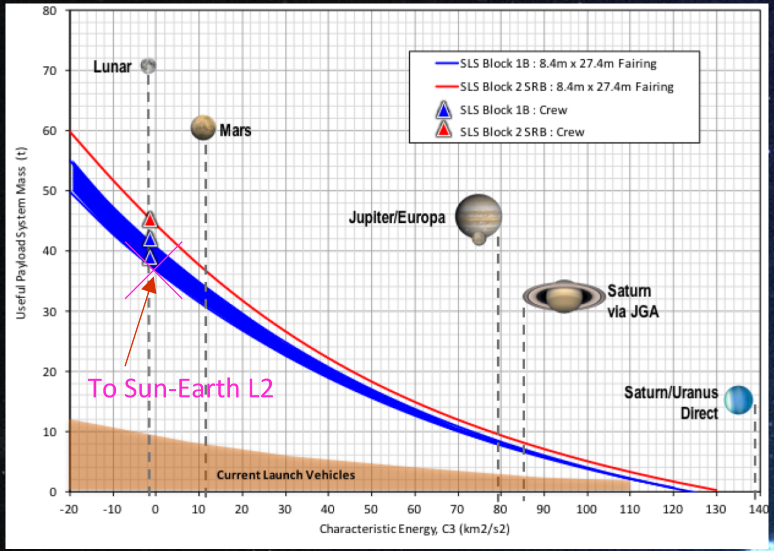



Figure 6-9. Composite 8.4 m PLF, Long Concept

*from HabEx interim report URS273294*

Key Specifications of Block 1B Cargo with 8.4m PLF, Long Concept:

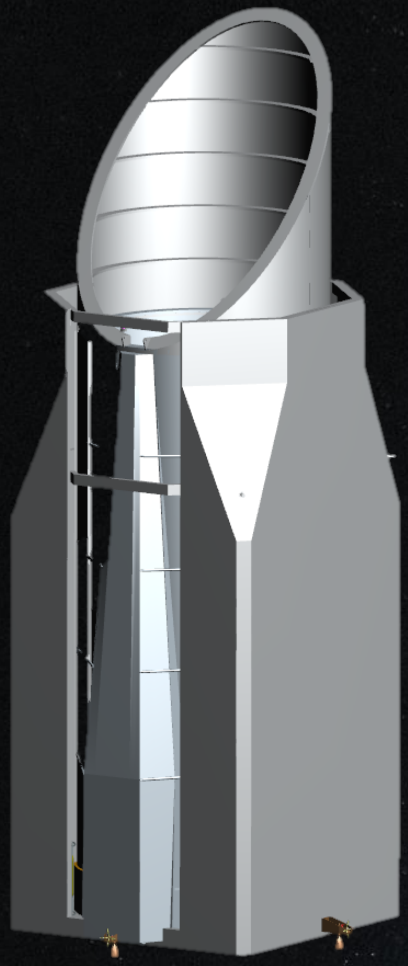
- 7.5m inner diameter fairing
- 25.83m total useable inner height
- ~36,000kg (minimum) to Sun-Earth L2



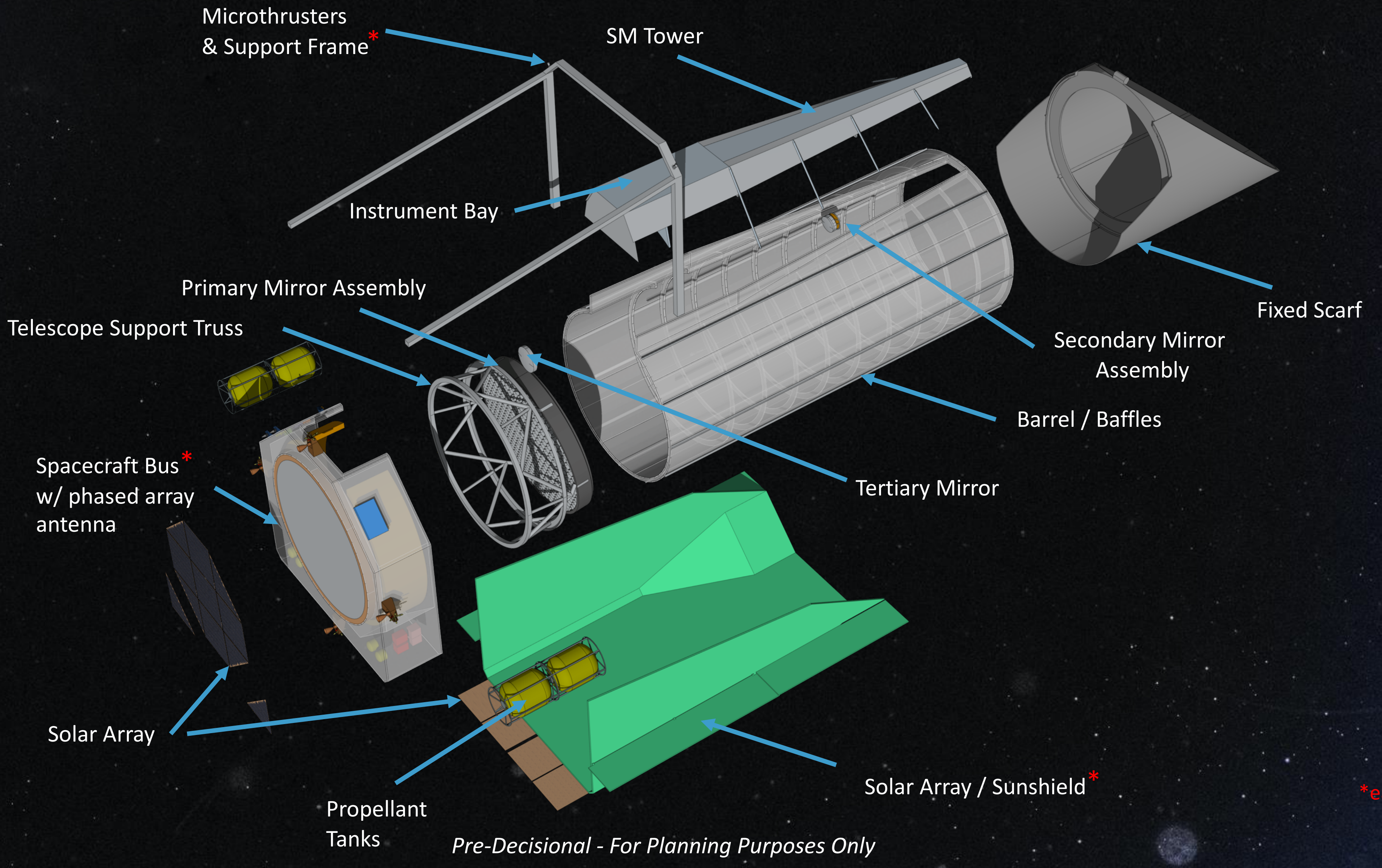

*Less complexity = less risk & less cost*

# Telescope Flight System Baseline Architecture

- Telescope Flight System:
  - Off-axis Three Mirror Anastigmat (TMA) telescope
    - 4-m monolithic primary mirror
    - Laser metrology and control truss
  - Four Science Instruments:
    - Coronagraph Imager w/spectrograph
    - Starshade Imager w/spectrograph
    - Workhorse Camera w/spectrograph
    - High Resolution UV Spectrograph
  - Attitude Determination and Control:
    - Fine Guider Subsystem w/four sensors
    - Microthrusters for fine pointing
    - Monoprop thrusters for slewing
  - Phased Array Antenna for communications
- Hubble Heritage:
  - Telescope coating: $MgF_2$ / Al (same as HST)
  - Telescope/Instrument bandpass: 115nm – 1800nm (as high as 2.5µm)
  - 3x the collecting area as Hubble



# Telescope Flight System: Exploded View (Baseline)




*earlier version

From CL#18-2217

*Pre-Decisional - For Planning Purposes Only*

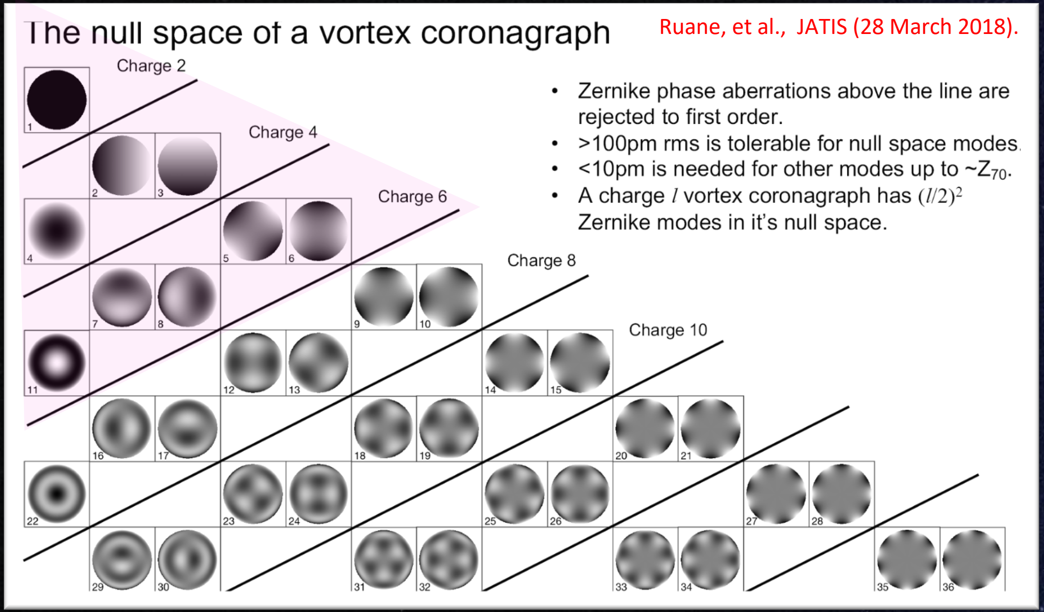
# Key Telescope Requirements

- The coronagraph instrument drives telescope requirements:

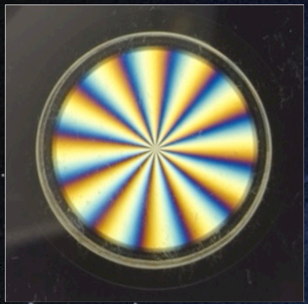
| Coronagraph Requirement | | Telescope Requirement | |
|---|---|---|---|
| Inner working angle (IWA) @ 500nm | 62mas | Aperture diameter | 4m |
| Contrast | $\leq 1x10^{-10}$ | Primary mirror f/# | f/2.5 |
| | | Diffraction limit wavelength | 400nm |
| | | Quasi-static WFE | 30nm rms |
| Maximize throughput | | Primary mirror type | monolith |
| | | Unobscured pupil | off-axis TMA |
| Contrast stability | $\leq 2x10^{-11}$ | Pointing stability | ≤2mas/axis |
| | | WFE stability | <1nm rms / 50hrs |

# Why Vector Vortex Coronagraph?

- Purpose:
  - to maximize planet light throughput and contrast and minimize requirements on the telescope
- Benefit:
  - Much less sensitive to low order telescope WFE
- Rationale:
  - Very good throughput and contrast:
    - on par (theoretically) with Hybrid-Lyot Coronagraphs (HLC) or other coronagraph types
  - Forgiving:
    - rejects low order Zernike WFE terms in its null space.
    - ~500pm rms instead of ~10pm rms stability
  - Demonstrated in the lab (though not to the level required for space)
  - Demonstrated on ground-based telescopes (Subaru, Palomar, VLT, Keck)
  - Further development on-going in HCIT at JPL




VVC6 IWA = 2.4$\lambda$/D = 62mas @ 500nm



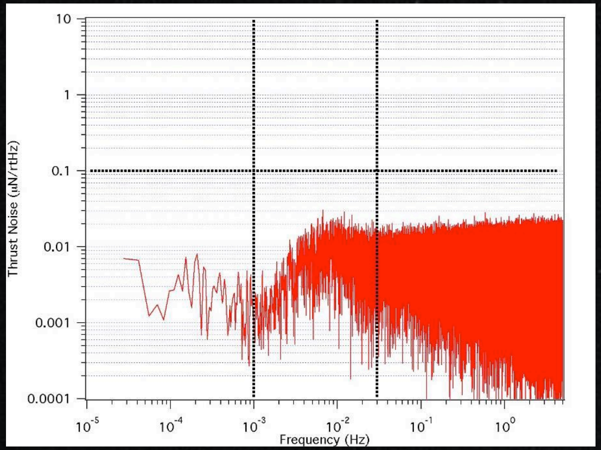
A charge 6 liquid crystal polymer vector vortex mask as seen through crossed polarizers.

From CL#18-2217

# Why Microthrusters?

- Purpose:
  - To maintain pointing during observations
  - To offset solar pressure induced torque on the telescope.
- Background:
  - Solar pressure ~1.5$\mu$N/m$^2$ at Sun-Earth L2.
  - HabEx has ~100m$^2$ projected area,
- Rationale:
  - Two flight proven microthrusters to choose from: cold gas and colloidal electrospray
    - Colloidal electrospray thrusters (NASA ST7) have flown on ESA LISA Pathfinder and are planned for ESA's LISA mission.
    - Cold gas thrusters are currently flying on ESA Gaia.
  - Colloidal Microthrusters (baselined) have sufficient thrust capability:
    - 5-30$\mu$N for each thruster head on ST7
    - Max thrust may increase to 60$\mu$N for LISA
    - thrust resolution ≦0.1$\mu$N
  - Significantly less noise than reaction wheels (≦0.03$\mu$N/rtHz over all frequencies)
  - Potentially higher reliability than reaction wheels
  - Simplifies structural dynamics design, analysis, and testing
  - Potentially no payload/spacecraft isolation.

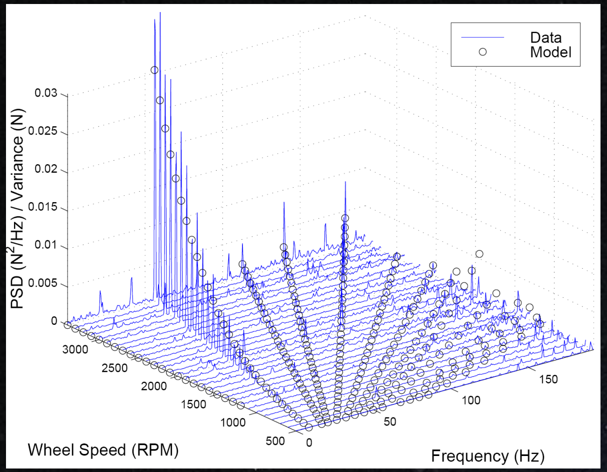
Units: µN/rtHz




Thruster noise PSD plot for colloidal microthrusters. Max noise above $10^{-3}$ is likely due to thrust-balance sensor noise limits.

(ref: *"Colloid Micro-Newton Thrusters For Precision Attitude Control", John Ziemer, et. al, April 2017, CL#17-2067*)

Units: N$^2$/Hz

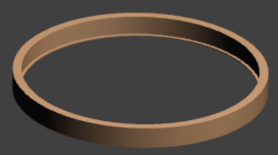



Waterfall plot derived from measured data showing Ithaco B-wheel Fx data and the radial force model
(reference: *"Conditioning, Reduction, and Disturbance Analysis of Large Order Integrated Models for Space-Based Telescopes"*
*By Scott Alan Uebelhart, MIT 2001*)

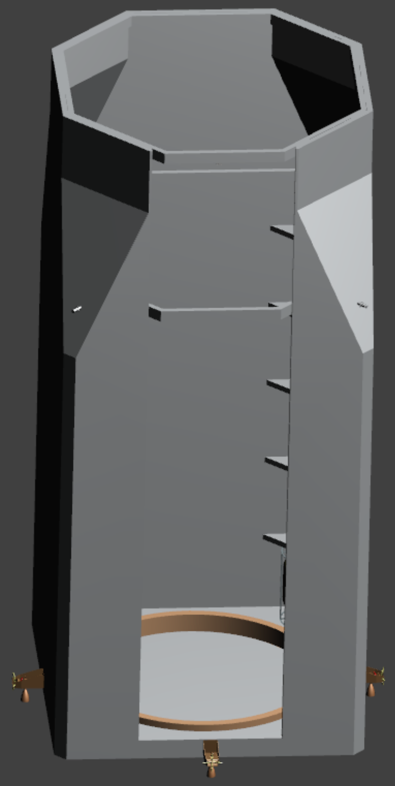
*Please note the different units. Square the vertical axis of the figure on the left.*

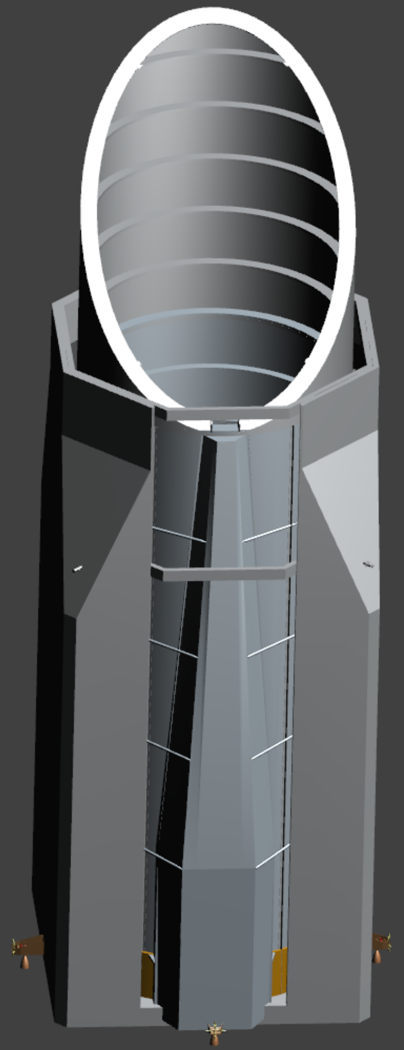
# Payload / Spacecraft / Launch Vehicle Interface

1) Interface Ring intersects with the payload, spacecraft, and launch vehicle



2) Interface ring incorporated into the spacecraft





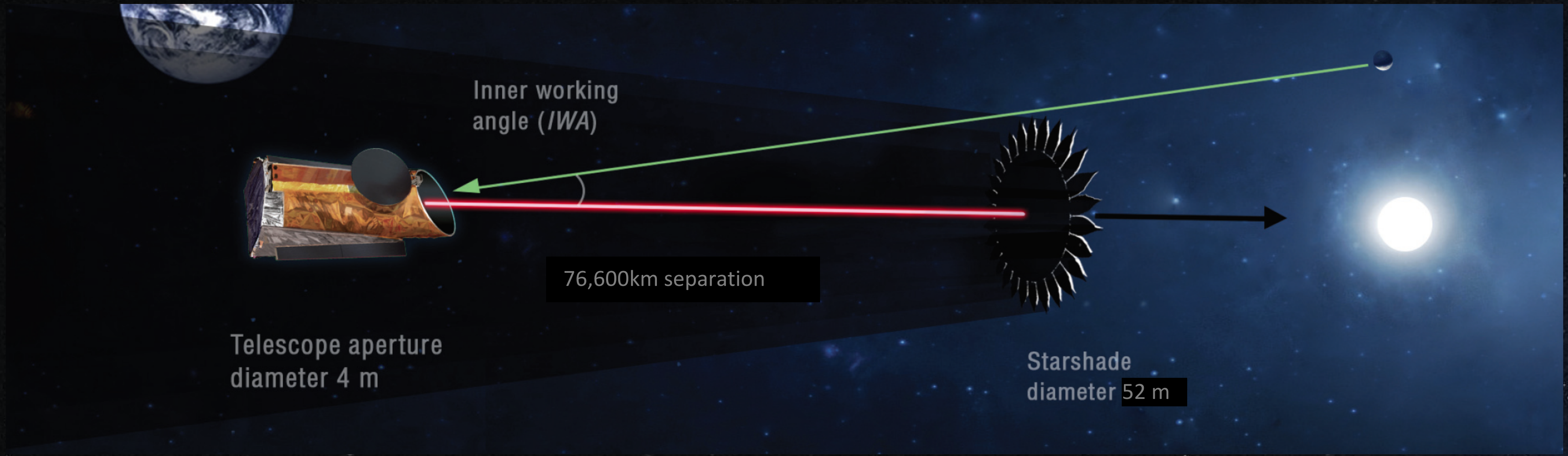
3) Payload sits directly on the interface ring, such that the spacecraft doesn't support the payload mass

# Why a Starshade?

- A starshade is designed for $<1\times10^{-10}$ contrast from the IWA+ over a wide spectral band.
- For HabEx:
  - Coronagraph @ 500nm, D=4m (Tel dia)
    - IWA = 2.4λ/D = 62mas
  - 52m Starshade @ 76,600km
    - IWA = 70mas over 300nm – 1000nm
  - For Coronagraph IWA=70mas @1000nm would require D = 7.1m

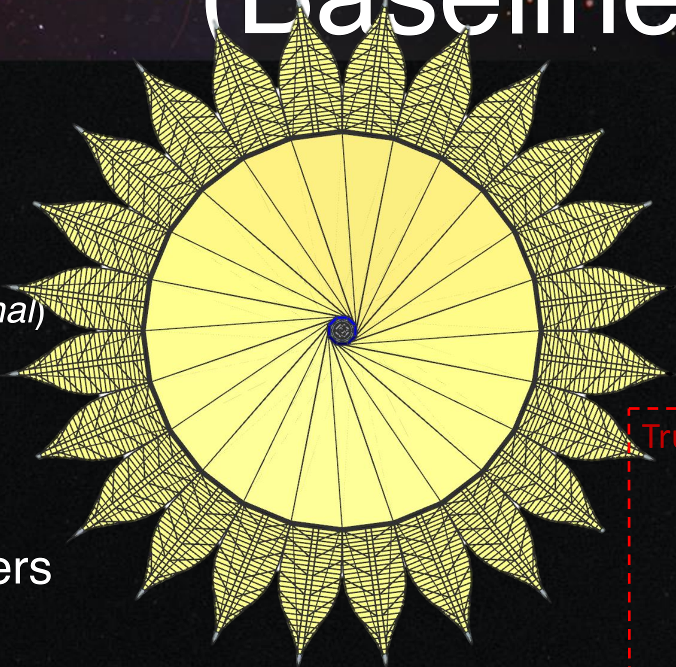
- The Starshade is slow to retarget, but is very good at deep spectral characterization at IWA with no OWA.
- The coronagraph is fast to retarget, but is only able to detect 500nm at IWA, and is limited by OWA
- These two exoplanet instruments are complementary.

- Starshade technologies are being developed by the Exoplanet Exploration Program
- A Starshade is planned for a rendezvous with WFIRST

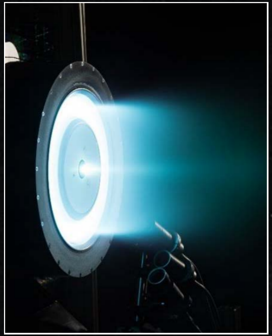


# Starshade Flight System (Baseline)

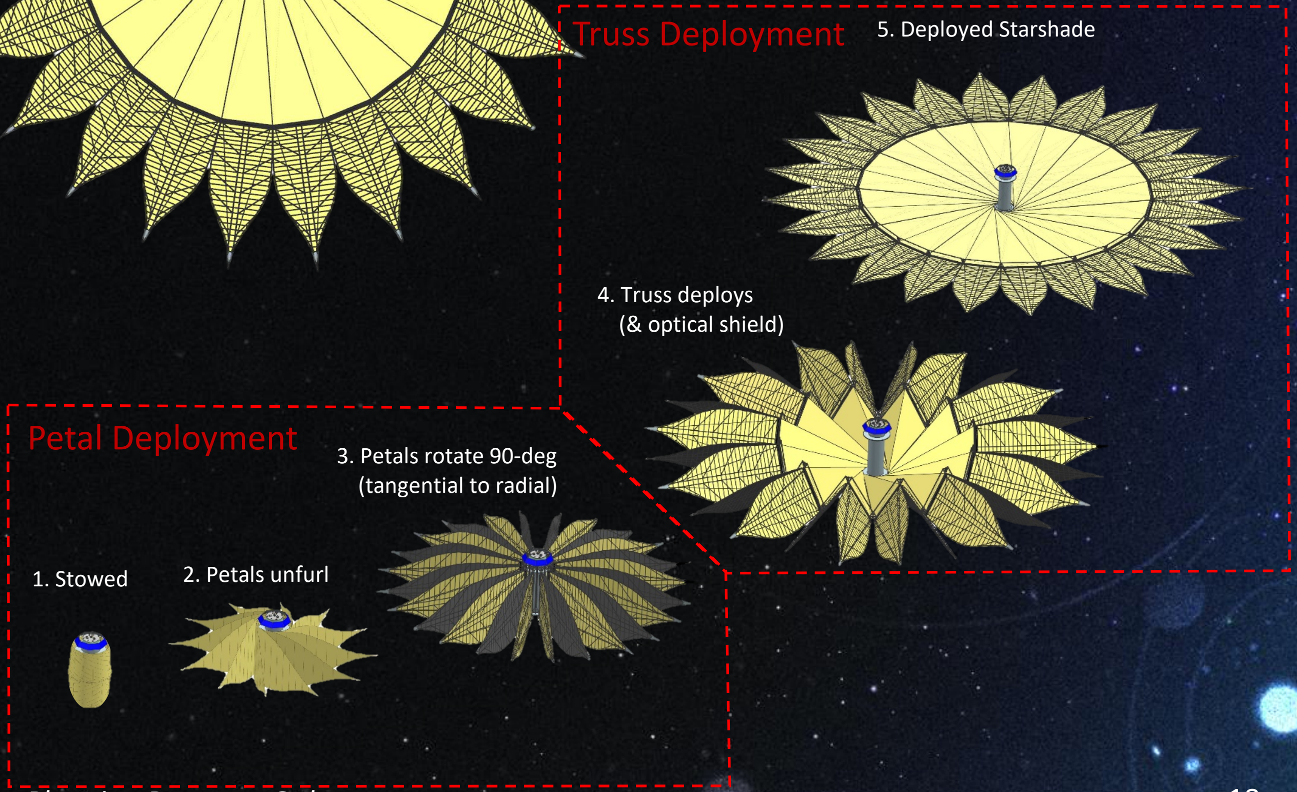
- 52-meter diameter (tip-to-tip)
  - 20-meter diameter central disk
  - 16-meter petals (x 24)
  - Vis: 300nm – 1000nm, 76,600km, 70mas IWA (*nominal*)
  - UV: 200nm – 667nm, 114,900km, 47mas IWA
  - NIR: 540nm – 1800nm, 42,500km, 126mas IWA



- Solar Electric Propulsion (SEP) Hall Effect thrusters
  - 2 flight + 1 spare, each side (6 total)
- Bi-prop hydrazine thrusters
  - ACS
  - Orbit maintenance



- Communications
  - X-band to ground, 1kbps, command & ranging
  - S-band to telescope, 100bps, data transfer & ranging



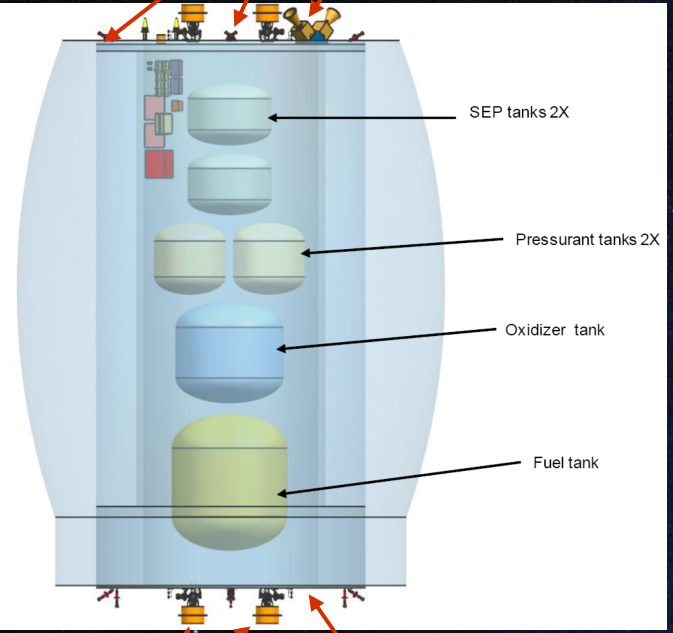

From CL#18-2217



From CL#18-3008

# Starshade Flight System (Baseline) Exploded View

- 52m diameter Starshade deploys radially from Hub exterior
- PLUS (Petal Launch Restraint & Unfurler Subsystem)
  - deploys the Starshade occulter (jettisoned after use)
- Starshade Bus fits within the Starshade Hub
- Bus Includes:
  - Solar Electric Propulsion (SEP) Hall effect thrusters
  - 2 Flight / 1 Spare (on each end)
  - Bi-prop chemical thrusters
  - Communications, with ground & telescope
  - Formation Flying beacon
  - Electronics
  - Solar Array (2 sets)
    - 1 rigid array on end of hub
    - 1 flexible CIGS array starshade disc when deployed
  - Thermal Control
- Starshade is spin-stabilized at 0.33 RPM
  - allows starshade occulter temperature to be passively controlled
- Communications same as telescope (w/o extra 1Tb storage)




From CL#18-2217

From CL#18-3008

# Technology/Engineering Needs

Technology:

- $\leq 10^{-10}$ contrast Coronagraph, with $\leq 2\times10^{-11}$ contrast stability
  - Including deformable mirrors
- Starshade petal shape deployment accuracy
- Starshade petal shape and position stability

Engineering:

- Demonstrate fabrication of a 4m monolithic primary mirror for space with existing capabilities

# Summary

- HabEx takes advantage of existing (or developing) technologies to achieve compelling science:
  - SLS Block 1B launch vehicle
    - Reduces complexity and technical risk (and cost)
  - Vector Vortex Coronagraph Charge 6
    - Relaxes telescope quality and stability requirements compared to other coronagraphs
  - Microthrusters
    - Significantly reduces mechanical noise
    - Simplifies structural dynamics design, analysis and test
  - Starshade
    - Allows for a smaller telescope (4m instead of 8m) to achieve the same level of exoplanet characterization over a broad spectral band
    - A smaller starshade design (~52 m) is being developed to improve technology readiness.